

SPIN-ORBIT COUPLINGS IN X-RAY BINARIES

Detailed calculations of mass transfer including tidal forces

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Abstract. We discuss the influence of tidal spin-orbit interactions on the orbital dynamics of close intermediate-mass X-ray binaries. In particular we consider here a process in which spin angular momentum of a contracting RLO donor star, in a synchronous orbit, is converted into orbital angular momentum and thus helps to stabilize the mass transfer by widening the orbit. Binaries which would otherwise suffer from dynamically unstable mass transfer (leading to the formation of a common envelope and spiral-in evolution) are thus shown to survive a phase of extreme mass transfer on a sub-thermal timescale. Furthermore, we discuss the orbital evolution prior to RLO in X-ray binaries with low-mass donors, caused by the competing effects of wind mass loss and tidal effects due to expansion of the (sub)giant.

1. Introduction

Tidal torques act to establish synchronization between the spin of the non-degenerate companion star and the orbital motion. Whenever the spin angular velocity of the donor is perturbed (by a magnetic stellar wind; or change in its moment of inertia due to either expansion or mass loss in response to RLO) the tidal spin-orbit coupling will result in a change in the orbital angular momentum leading to orbital shrinkage or expansion.

We have performed detailed numerical calculations of the non-conservative evolution of ~ 200 close binary systems with $1.0 - 5.0 M_{\odot}$ donor stars and a $1.3 M_{\odot}$ accreting neutron star. Rather than using analytical expressions for simple polytropes, we calculated the thermal response of the donor star to mass loss, using an updated version of Eggleton's numerical computer code, in order to determine the stability and follow the evolution of the mass transfer. We refer to Tauris & Savonije (1999) for a more detailed description of the computer code and the binary interactions considered.

2. The orbital angular momentum balance equation

Consider a circular¹ binary with an (accreting) neutron star and a companion (donor) star with mass M_{NS} and M_2 , respectively. The orbital angular momentum is given by: $J_{\text{orb}} = (M_{\text{NS}} M_2 / M) \Omega a^2$, where $M = M_{\text{NS}} + M_2$ and $\Omega = \sqrt{GM/a^3}$ is the orbital angular velocity. A simple logarithmic differentiation of this equation yields the rate of change in orbital separation:

$$\frac{\dot{a}}{a} = 2 \frac{\dot{J}_{\text{orb}}}{J_{\text{orb}}} - 2 \frac{\dot{M}_{\text{NS}}}{M_{\text{NS}}} - 2 \frac{\dot{M}_2}{M_2} + \frac{\dot{M}_{\text{NS}} + \dot{M}_2}{M} \quad (1)$$

where the total change in orbital angular momentum can be expressed as:

$$\frac{\dot{J}_{\text{orb}}}{J_{\text{orb}}} = \frac{\dot{J}_{\text{gwr}}}{J_{\text{orb}}} + \frac{\dot{J}_{\text{mb}}}{J_{\text{orb}}} + \frac{\dot{J}_{\text{ls}}}{J_{\text{orb}}} + \frac{\dot{J}_{\text{ml}}}{J_{\text{orb}}} \quad (2)$$

The first term on the right side of this equation governs the loss of J_{orb} due to gravitational wave radiation (Landau & Lifshitz 1958). The second term arises due to a combination a magnetic wind of the (low-mass) companion star and a tidal synchronization (locking) of the orbit. This mechanism of exchanging orbital into spin angular momentum is referred to as magnetic braking (see e.g. Verbunt & Zwaan 1981; Rappaport et al. 1983).

2.1. TIDAL TORQUE AND DISSIPATION RATE

The third term in eq.(2) was recently discussed by Tauris & Savonije (1999) and describes possible exchange of angular momentum between the orbit and the donor star due to its expansion or mass loss (note, we have neglected the tidal effects on the gas stream and the accretion disk). For both this term and the magnetic braking term we estimate whether or not the tidal torque is sufficiently strong to keep the donor star synchronized with the orbit. We estimate the tidal torque due to the interaction between the tidally induced flow and the convective motions in the stellar envelope by means of the simple mixing-length model for turbulent viscosity $\nu = \alpha H_p V_c$, where the mixing-length parameter α is adopted to be 2 or 3, H_p is the local pressure scaleheight, and V_c the local characteristic convective velocity. The rate of tidal energy dissipation can be expressed as (Terquem et al. 1998):

$$\frac{dE}{dt} = -\frac{192\pi}{5} \Omega^2 \int_{R_i}^{R_o} \rho r^2 \nu \left[\left(\frac{\partial \xi_r}{\partial r} \right)^2 + 6 \left(\frac{\partial \xi_h}{\partial r} \right)^2 \right] dr \quad (3)$$

where the integration is over the convective envelope and Ω is the orbital angular velocity, i.e. we neglect effects of stellar rotation. The radial and

¹This is a good approximation since tidal effects acting on the near RLO giant star will circularize the orbit on a short timescale of $\sim 10^4$ yr, cf. Verbunt & Phinney (1995).

horizontal tidal displacements are approximated here by the values for the adiabatic equilibrium tide:

$$\xi_r = f r^2 \rho \left(\frac{dP}{dr} \right)^{-1} \quad \xi_h = \frac{1}{6r} \frac{d(r^2 \xi_r)}{dr} \quad (4)$$

where for the dominant quadrupole tide ($l=m=2$) $f = -GM_2/(4a^3)$.

The locally dissipated tidal energy is taken into account as an extra energy source in the standard energy balance equation of the star, while the corresponding tidal torque follows as: $\Gamma = -(1/\Omega)(dE/dt)$.

The thus calculated tidal angular momentum exchange $dJ = \Gamma dt$ between the donor star and the orbit during an evolutionary timestep dt is taken into account in the angular momentum balance of the system. If the so calculated angular momentum exchange is larger than the amount required to keep the donor star synchronous with the orbital motion of the compact star we adopt a smaller tidal angular momentum exchange (and corresponding tidal dissipation rate) that keeps the donor star exactly synchronous.

2.2. SUPER-EDDINGTON ACCRETION AND ISOTROPIC RE-EMISSION

The last term in eq.(2) is the most dominant contribution and is caused by loss of mass from the system (see e.g. van den Heuvel 1994; Soberman et al. 1997). We have adopted the "isotropic re-emission" model in which all of the matter flows over, in a conservative way, from the donor star to an accretion disk in the vicinity of the neutron star, and then a fraction, β of this material is ejected isotropically from the system with the specific orbital angular momentum of the neutron star. If the mass-transfer rate exceeds the Eddington accretion limit for the neutron star $\beta > 0$. In our calculations we assumed $\beta = \max[0, 1 - \dot{M}_{\text{Edd}}/\dot{M}_2]$ and $\dot{M}_{\text{Edd}} = 1.5 \times 10^{-8} M_\odot \text{ yr}^{-1}$.

3. Evolution neglecting spin-orbit couplings

Assuming $\dot{J}_{\text{gwr}} = \dot{J}_{\text{mb}} = \dot{J}_{\text{ls}} = 0$ and $\dot{J}_{\text{ml}}/J_{\text{orb}} = \beta q^2 \dot{M}_2/(M_2(1+q))$ one obtains easily analytical solutions to eq.(1). In Fig. 1 we have plotted

$$-\frac{\partial \ln(a)}{\partial \ln(q)} = 2 + \frac{q}{q+1} + q \frac{3\beta - 5}{q(1-\beta) + 1} \quad (5)$$

as a function of the mass ratio $q = M_2/M_{\text{NS}}$. The sign of this quantity is important since it tells whether the orbit expands or contracts in response to mass transfer (note $\partial q < 0$). We notice that the orbit always expands when $q < 1$ and it always decreases when $q > 1.28$ [solving $\partial \ln(a)/\partial \ln(q) = 0$ for $\beta = 1$ yields $q = (1 + \sqrt{17})/4 \approx 1.28$]. If $\beta > 0$ the orbit can still expand for $1 < q \leq 1.28$. Note, $\partial \ln(a)/\partial \ln(q) = 2/5$ at $q = 3/2$ independent of β .

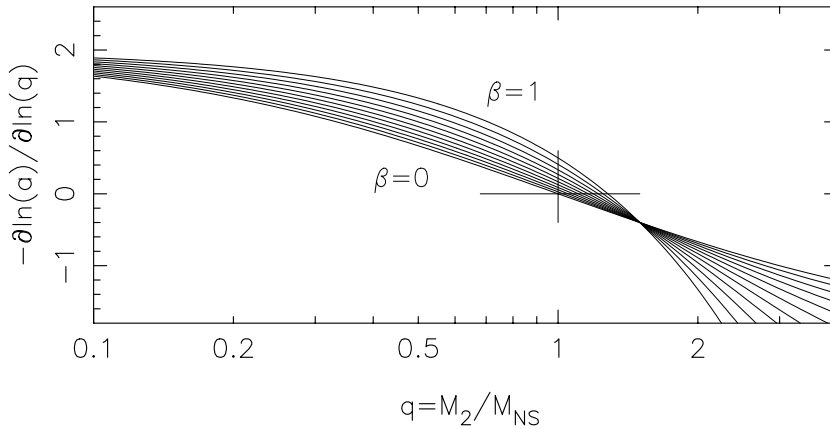


Figure 1. $-\partial \ln(a)/\partial \ln(q)$ as a function of q for X-ray binaries. The different curves correspond to different constant values of β in steps of 0.1. Tidal effects were not taken into account here. A cross is shown to highlight the case of $q = 1$ or $\partial \ln(a)/\partial \ln(q) = 0$. The evolution during the mass-transfer phase follows these curves from right to left since M_2 and q are decreasing with time (though β need not be constant).

4. Results including tidal spin-orbit couplings

In Fig. 2 we have plotted the orbital evolution of an X-ray binary. The solid lines show the evolution including tidal spin-orbit interactions and the dashed lines show the calculations without these interactions. In all cases the orbit will always decrease initially as a result of the large initial mass ratio ($q = 4.0/1.3 \simeq 3.1$). But when the tidal interactions are included the effect of pumping angular momentum into the orbit (at the expense of spin angular momentum) is clearly seen. The tidal locking of the orbit acts to convert spin angular momentum into orbital angular momentum causing the orbit to widen (or shrink less) in response to mass transfer/loss. The related so-called Pratt & Strittmatter (1976) mechanism has previously been discussed in the literature (e.g. Savonije 1978). Including spin-orbit interactions many binaries will survive an evolution which may otherwise end up in an unstable common envelope and spiral-in phase. An example of this is seen in Fig. 2 where the binary with initial $P_{\text{orb}} = 2.5$ days (solid line) only survives as a result of the spin-orbit couplings. The dashed line terminating at $M_2 \sim 3.0 M_\odot$ indicates the onset of a run-away mass-transfer process ($\dot{M}_2 > 10^{-3} M_\odot \text{ yr}^{-1}$) and formation of a common envelope and possible collapse of the neutron star into a black hole. In fact, many of the systems with $2.0 < M_2/M_\odot < 5.0$ recently studied by Tauris, van den Heuvel & Savonije (2000) would not have survived the extreme mass-transfer phase if the spin-orbit couplings had been neglected.

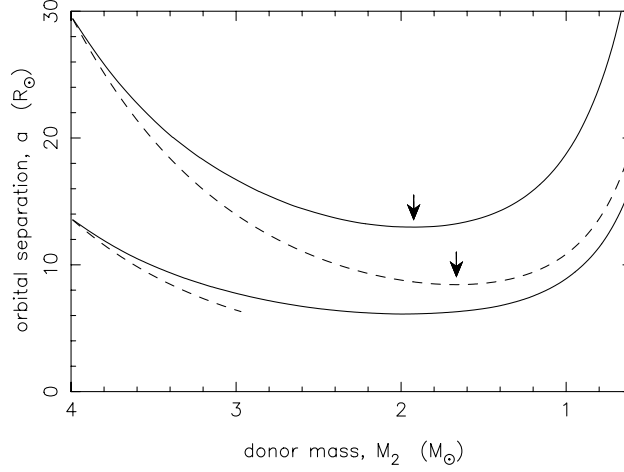


Figure 2. Evolution of orbital separation as a function of donor star mass during the RLO phase in a binary with $M_2 = 4.0 M_\odot$ ($X=0.70$, $Z=0.02$, $\alpha=2.0$), $M_{\text{NS}} = 1.3 M_\odot$ and $P_{\text{orb}} = 8.0$ and 2.5 days, top and bottom lines respectively. The lifetime of these X-ray binaries are only $t_X = 1.2$ and 2.1 Myr, respectively. The solid evolutionary tracks were calculated including tidal interactions and the dashed lines without. See text for details.

The location of the minimum orbital separations in Fig. 2 are marked by arrows in the case of $P_{\text{orb}} = 8.0$ days. Since the mass-transfer rates in such an intermediate-mass X-ray binary are shown to be highly super-Eddington (Tauris, van den Heuvel & Savonije 2000) we have $\beta \approx 1$. Hence in the case of neglecting the tidal interactions (dashed line) we expect to find the minimum separation when $q = 1.28$ (cf. Section 3). Since the neutron star at this stage only has accreted $\sim 10^{-4} M_\odot$ we find that the minimum orbital separation is reached when $M_2 = 1.28 \times 1.30 M_\odot = 1.66 M_\odot$. Including tidal interactions (solid line) results in an earlier spiral-out in the evolution and the orbit is seen to widen when $M_2 \leq 1.92 M_\odot$ ($q \approx 1.48$).

4.1. LOW-MASS DONORS AND PRE-RLO ORBITAL EVOLUTION

For low-mass ($\leq 1.5 M_\odot$) donor stars there are two important consequences of the spin-orbit interactions which result in a reduction of the orbital separation: magnetic braking and expansion of the (sub)giant companion star. In the latter case the conversion of orbital angular momentum into spin angular momentum is caused by a reduced rotation rate of the donor. However, in evolved stars there is a significant wind mass loss (Reimers 1975) which will cause the orbit to widen and hence there is a competition between this effect and the tidal spin-orbit interactions for determining the

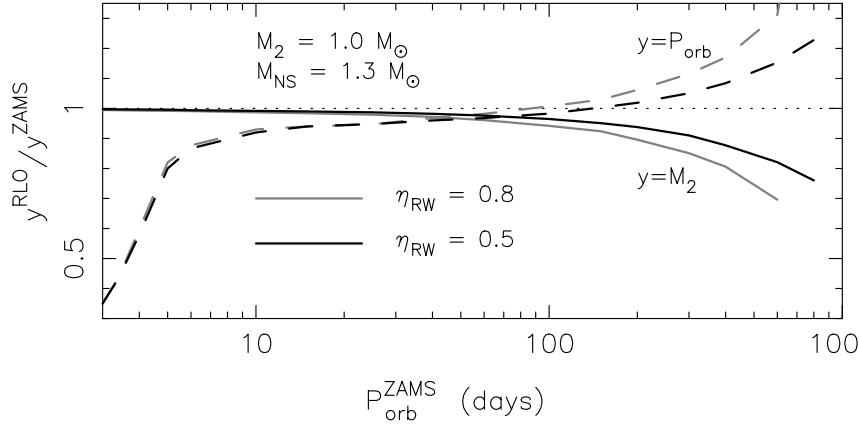


Figure 3. The changes of donor mass, M_2 (full lines) and orbital period, P_{orb} (dashed lines), due to wind mass loss and tidal spin-orbit interactions, from the ZAMS until the onset of the RLO as a function of the initial orbital period of a circular binary.

orbital evolution prior to the RLO-phase. This is demonstrated in Fig. 3. We assumed $\dot{M}_{2\text{wind}} = -4 \times 10^{-13} \eta_{\text{RW}} L R_2 / M_2 M_{\odot} \text{ yr}^{-1}$ where the mass, radius and luminosity are in solar units and η_{RW} is the mass-loss parameter. It is seen that only for binaries with $P_{\text{orb}}^{\text{ZAMS}} > 100$ days will the wind mass loss be efficient enough to widen the orbit. For shorter periods the effects of the spin-orbit interactions dominate (caused by expansion of the donor) and loss of orbital angular momentum causes the orbit to shrink. This result is very important e.g. for population synthesis studies of the formation of millisecond pulsars, since P_{orb} in some cases will decrease significantly prior to RLO. As an example a system with $M_2 = 1.0 M_{\odot}$, $M_{\text{NS}} = 1.3 M_{\odot}$ and $P_{\text{orb}}^{\text{ZAMS}} = 3.0$ days will only have $P_{\text{orb}}^{\text{RLO}} = 1.0$ days at the onset of the RLO.

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